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HBOI Underwater Imaging and Communications Research – Phase I

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LONG-TERM GOALS

The long term goal of this program is to advance understanding of multistatic laser line scan (LLS) imaging and networking techniques and their applicability to Navy missions which utilize multiple UUVs in support of littoral operations. The planned three year outcome of the work is to provide a validated radiative transfer simulation suite which can allow underwater laser imaging and communications system developers or operators to predict imaging or communication system performance for alternate configurations of bistatic or multistatic UUV based LLS networks under known environmental conditions.

OBJECTIVES

The FY2009 effort is focused on several objectives:

1) **Development of benchtop hardware for bistatic LLS imaging and short pulse one-way and two-way time history measurements.**
The objective is to experimentally investigate the performance of the bistatic imaging technique in specific geometries, examining degradation due to volumetric scatter in known scattering suspensions and devising robust image formation techniques. Both on-axis and off-axis one-way pulse propagation measurements over extended distances (up to 13 meters) have been conducted. The acquired datasets will be used to assist with the development and validation of the one-way and two-way radiative transfer codes.

2) **Development of one-way pulse stretching radiative transfer code.** The objective is to develop a semi-analytical numerical implementation of a one-way channel model that can rapidly and accurately simulate the propagation of coded pulse trains or intensity modulated electro-optical signals in turbid ocean environments. The models will be used to estimate pulse stretching and/or loss of modulation depth for user-configurable electro-optical

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communications systems as a function of water Inherent Optical Properties (IOPs). The analytical nature of the model will also provide insight into the physical mechanisms that give rise to temporal dispersion and their relative importance when considering the various techniques under investigation.

3) **Development of bistatic laser pulse time history and LLS image simulation code.** The objective is to use the semi-analytic model as the basis for a two-way bistatic time history and image simulation model, which allows the user to specify the laser-target-receiver geometry, laser and receiver angular and spatial apertures, inherent optical properties (IOPs) and the target bidirectional reflectance distribution function (BRDF).

4) **Conduct small angle measurement of near-forward polarized light field** The objective is to develop an understanding of near-forward (0° - 20°) depolarization with fine angular resolution in various natural and manipulated particle suspensions, in order to establish the potential benefit of using polarization-sensitive receivers for enhancing performance of the techniques under investigation.

5) **Develop methods and conduct simulations to investigate enabling technologies for multistatic LLS networks:**
    a. investigate the use of laser multilateration techniques for localization of multiple illuminators operating over a region of seabed.
    b. investigate non line-of-sight communication and image synchronization techniques suited for muti-static imaging and communications scenarios.

APPROACH

The approach for meeting these objectives within this funding period involved collaborations with Drs. Tom Giddings and Joe Shirron at Metron Inc. (Reston, VA) for expertise in electro-optic system performance and radiative transfer modeling; Dr Yogesh Agrawal at Sequoia Scientific Inc. (Bellevue, WA) for development of a polarization-sensitive forward-scattering meter; Professor Kenneth Voss at University of Miami (Coral Gables, FL) for measurement of test target BRDF; Dr Charles Mazel at Physical Sciences Inc. (Andover, MA) for independent data and image analysis.

The experimental effort makes use of the large laser test facility within the Ocean Visibility and Optics Laboratory at the Harbor Branch campus of Florida Atlantic University. Imaging and communications system hardware and the custom testing fixtures required to make the experimental measurements are being developed by engineers and technicians at Harbor Branch under the guidance of Drs. Dalgleish and Caimi.

WORK COMPLETED

Test hardware: The HBOI test facility has been upgraded to include multiple viewports within the three optics labs around the perimeter of the tank. A four degrees-of-freedom robotic positioning system has been designed, constructed and installed to precisely position targets and illuminators within the volume of the tank. A benchtop bistatic LLS system has been assembled and demonstrated. Bistatic imaging and short pulse time history measurements have been performed. Results were compared to a less complex camera and light bistatic imaging system in the same geometry.

Radiative Transfer Modeling: The first phase of the development for the analytical model for temporal dispersion is nearly completed. This phase establishes the methodology for estimating the effects of geometric spreading on time-dependent light beam propagation. The goal is to derive a multiple time-scales expansion for electro-optical signal propagation in a turbid environment. For the first phase, which considers geometric spreading but not scattering, the exact result can be formally derived using Green's function techniques. The exact analytical solution and Monte Carlo simulations will be used to validate the multiple-scales approximation. Once the appropriate multiple-scales methodology has been established, the analytical expansion will be enlarged to include the effects of multiple scattering on electro-optical signal propagation.

BRDF measurements: Unpolarized wet BRDF measurements have been made with the technical target to be used for bistatic imaging tests.

Polarized Forward-Scatter Meter: Hardware has been selected to modify the off-the-shelf LISST-100X to simultaneously measure cross and co-polarization of the forward scattered field. Initial experiments are currently being performed. A Mie scattering model (Bohren and Huffman, 1983) computing the polarization state of particle backscattering and optical system (Yang *et al*, 2003) is currently being modified to compute the Mueller matrix of the near-forward-scattering particles along with rotation matrices of the optical system. This model will be used to compare theoretical models with measurements and to predict the performance of optical systems capable of controlling and analyzing the Stokes parameters of the input and output fields respectively.

Laser multilateration: A simulation framework has been developed to examine one-way and two-way laser multilateration using a Difference Time of Arrival (DTOA) algorithm.

RESULTS

BRDF measurements were carried out by Professor Kenneth Voss using a previously developed instrument (Voss *et al*, 2000), which allows simultaneous radiance measurements at more than a hundred viewing angles. The collimated incident irradiance could be oriented in eight incident angles to the sample surface, using two wavelengths of radiation. For these experiments, the target was submerged in water.

The purpose of these measurements was to obtain experimental data to be used as an input to the radiative transfer model for validation. While many surfaces are considered to be Lambertian, i.e. the detected radiance is independent from the viewing angle, this has been shown not to be the case for most reflecting surfaces underwater. With the current work, the angle between the incident and the measured irradiance (phase angle) varies due to the target orientation and the scanning angle, making the radiance distribution a significant factor for the two-way radiative transfer calculation. This is illustrated in Figure 1, where the reflectance factor shows distinct dependence on the phase angle, and also indicates strong specular component in the detected radiation. Furthermore, there is an observable difference in the radiance distribution when two distinct regions (black and white) of the USAF 1951 target are compared. The BRDF files will be used as an input to the bistatic LLS image simulation code during validation exercises.

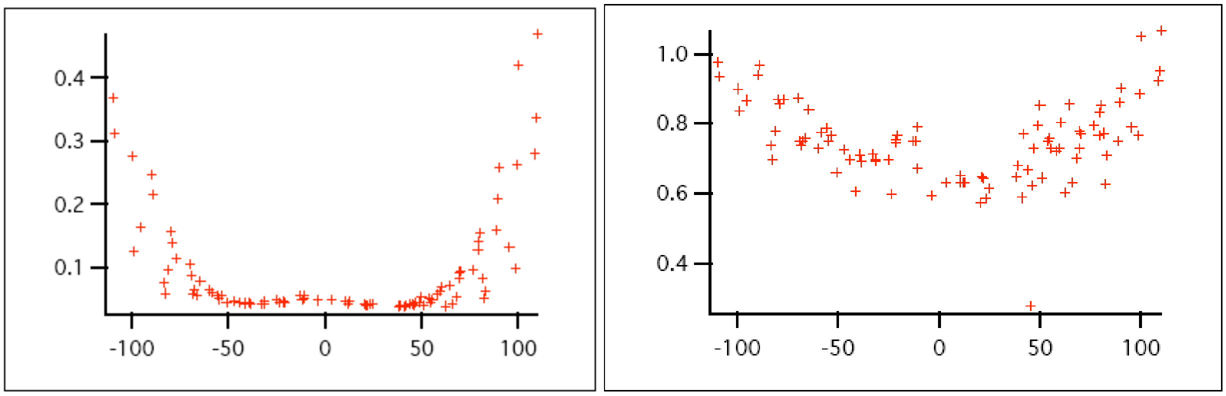

Figure 1. Measured BRDF of the USAF 1951 B/W target at 45 degrees incident angle. The image on the left shows the magnitude of the reflectance factor (REFF, vertical axis) as a function of the phase angle (in degrees, horizontal axis) of a black part of the target, while the image on the right shows the corresponding REFF values of a white part of the target.

Bistatic image results are shown in figure 2. The image results from the 2m laser-to-target case show a much more severe contrast degradation and loss of resolution due to volumetric backscatter and laser-to-target forward scatter. At 27 target-to-receiver beam attenuation lengths, the 2m case has almost reached a limit whereas the 0.5m case can still produce a high contrast, low noise image at 33 target-to-receiver beam attenuation lengths. Contrast plots derived from laser pulse time history measurements from both 10% and 99% reflectance Spectralon test panels also show the more rapid contrast reduction with greater laser-to-target distances at high scattering coefficients. To compare with the bistatic LLS results, an intensified CCD camera and powerful lamp combination were also used in the same bistatic geometry to determine the relative performance of this less complex system alternative. These results indicated that even for the 0.25m laser-to-target distance, the Spectralon split target became contrast limited at a c value of $0.75m^{-1}$ (i.e. less than 8 target-to-receiver beam attenuation lengths).

For smaller laser-to-target distances the high quality imagery obtainable indicates that such bistatic or multistatic LLS system architectures would be able to provide images useful for an operator to perform target identification over significant distances in turbid conditions. For example, in turbid coastal conditions ($c=1m^{-1}$) 33 target-to-receiver beam attenuation lengths represents 33m (>100ft) from target to receiver, which could mean from seabed to surface in shallow water operations. However, to fully understand the potential of the bistatic LLS technique in natural waters, it is intended to perform more experiments with realistic albedos and to develop an accurate radiative transfer model, which also includes forward scatter glow noise due to laser-to-target beam spreading and pulse stretching for both volumetric scatter and target signals.

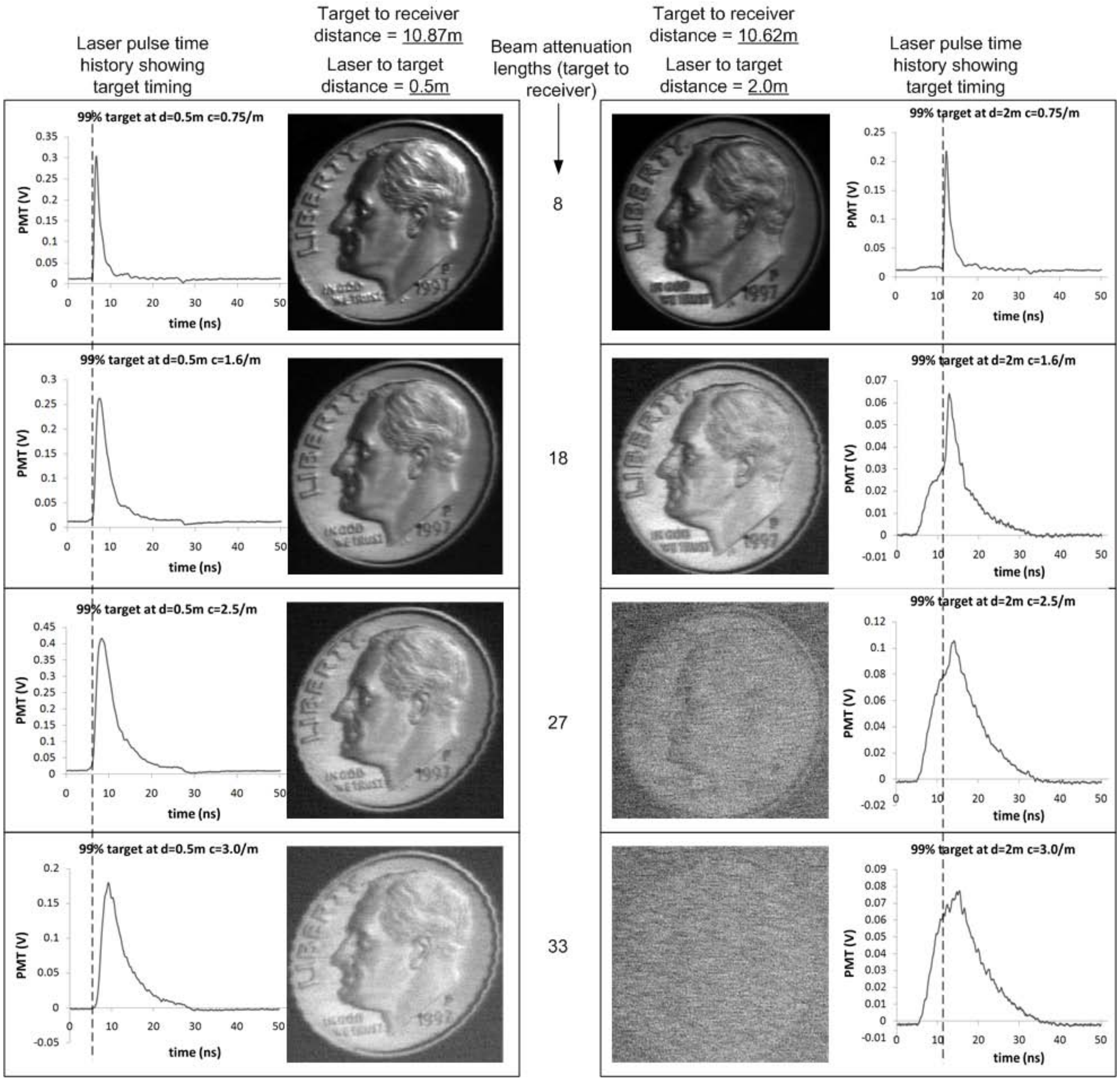

Figure 2. Bistatic LLS extended range (10.62 – 10.87m) image data of dime coin on imaging target at laser-to-target distances of 0.5m (left columns) and 2m (right columns), with CW laser power 130mW as a function of target to receiver beam attenuation lengths.. Laser pulse time history data from near-identical geometrical and environmental conditions is also shown next to each image.

IMPACT/APPLICATIONS

In the long term the multistatic LLS techniques under study, once developed and deployed with swarms of co-operating UUVs may have the *potential to provide identification-quality underwater imagery in real-time across much greater regions of seabed than current technology allows.*

In the near term, the radiative transfer model being developed under this program could have significant use for the Navy in analyzing potential performance of the multistatic LLS methodology in alternate scenarios. The model could also be used in the design of optimal platforms, operational schemes and dual purpose imaging/communications system component selection.

RELATED PROJECTS

A Navair SBIR phase II is been performed in collaboration with Advanced Technologies Group (Stuart, FL) to develop a high speed gated Lidar-radar receiver for modulated-pulse LLS underwater imaging.

A project being performed at HBOI as part of the HBOI/FAU NOAA Co-operative Institute for Ocean Exploration, Research and Technology has the objectives of developing swarm robotic approaches to underwater *in situ* sensing tasks.

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